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Effects of forefoot bending elasticity of running shoes on gait and running performance

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ABSTRACT

The aim of this study was to investigate the effects of forefoot bending elasticity of running shoes on kinetics and kinematics during walking and running. Twelve healthy male participants wore normal and elastic shoes while walking at 1.5 m/s, jogging at 2.5 m/s, and running at 3.5 m/s. The elastic shoes were designed by modifying the stiffness of flexible shoes with elastic bands added to the forefoot part of the shoe sole. A Kistler force platform and Vicon system were used to collect kinetic and kinematic data during push-off. Electromyography was used to record the muscle activity of the medial gastrocnemius and medial tibialis anterior. A paired dependent *t*-test was used to compare the various shoes and the level of significance was set at $\alpha = .05$. The range of motion of the ankle joint and the maximal anterior–posterior propulsive force differed significantly between elastic and flexible shoes in walking and jogging. The contact time and medial gastrocnemius muscle activation in the push-off phase were significantly lower for the elastic shoes compared with the flexible shoes in walking and jogging. The elastic forefoot region of shoes can alter movement characteristics in walking and jogging. However, for running, the elasticity used in this study was not strong enough to exert a similar effect.

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1. Introduction

Improving forefoot push-off facilitates the augmentation of forward acceleration and ultimately enhances athletic performance (Goldmann, Sanno, Willwacher, Heinrich, & Brüggemann, 2011; Hunter, Marshall, & McNair, 2005). The stance phase in gait is divided equally into passive and active phases (Neptune, Kautz, & Zajac, 2001; Nishiwaki, 2008). The key factor that influences the active phase is the forefoot push-off; however, current studies regarding footwear design and the feet have mostly emphasized heel shock absorption (Bonacci et al., 2013) and have rarely focused on the role that the forefoot plays in lower limb locomotion (Lieberman, 2012; Lieberman et al., 2010). Consequently, research and development concerning the forefoot region of shoes is frequently neglected. Furthermore, in various competitive sports, sport shoes with appropriate forefoot characteristics can improve athletic performance (Stefanyshyn & Fusco, 2004; Stefanyshyn & Nigg, 2000). Functions of the forefoot are not related only to push-off performance but are also reflected by how the forefoot lands, which can cause numerous sports injuries related to the forefoot (Willems, De Ridder, & Roosen, 2012; Willems, Witvrouw, Delbaere, De Cock, & De Clercq, 2005). By using various forefoot landing approaches, the conduction of force and torque can be changed, thereby reducing the risk of injuries (De Wit, De Clercq, & Aerts, 2000). Therefore, enhancing the forefoot design by increasing the bending stiffness of shoes can improve athletic performance and prevent sports injuries (Nigg, 2009).

Studies have indicated that modifying the flexibility in the forefoot region of running shoes provides a greater range of motion for the forefoot and increases the activation of the shank muscles. In addition, long-term use of flexible running shoes strengthens the shank muscles substantially (Bruggemann, Potthast, Braunstein, & Niehoff, 2005; Goldmann, Sanno, Willwacher, Heinrich, & Bruggemann, 2013). Previous research targeting the forefoot region has shown that through material cutting or slicing, a greater movement angle in the metatarsophalangeal joint (MPJ) can be achieved, which subsequently enhances the muscle activity of the gastrocnemius muscle (Chen, Hsieh, Shih, & Shiang, 2012). The same study also suggested that enhancing the bending elasticity of running-shoe soles can reduce the activity of certain muscles (Chen et al., 2012).

In previous studies, changes have been applied to shoe materials to alter the ground reaction force patterns in human locomotion (Reenalda, Freriks, & Buurke, 2011). Several studies have also asserted that by using a certain material in shoe soles that provides the forefoot with greater bending elasticity, the dissipation of applied forces is diminished (Lin et al., 2013; Stefanyshyn & Nigg, 1998) without changing the joint angle of the lower extremity (Stefanyshyn & Nigg, 2000). Consequently, this optimizes the force conduction efficiency, which improves performance in jumping and landing (Stefanyshyn & Nigg, 1998, 2000; Tinoco, Bourgit, & Morin, 2010). However, other studies have indicated that increasing the bending elasticity of shoe soles does not enhance jumping performance (Toon, Vinet, Pain, & Caine, 2011). Studies on forefoot designs have typically focused on increasing the insole stiffness (Tinoco et al., 2010; Willwacher, König, Potthast, & Brüggemann, 2013). This type of design might also increase the forefoot pressure and the contact between the foot portion and the elastic material might reduce deformation of the material and consequently constrain its ductility. In this study, elastic materials were added to the outsoles of shoes in the forefoot region to maximize energy return. Consequently, we expected an increase in the bending elasticity in the forefoot region of the shoes to improve the energy return effect and alter the kinetics of the push-off phase. Therefore, we compared the forefoot push-off phase of walking and running at moderate intensities and different gait speeds by using two types of shoe with varying forefoot bending elasticity. The hypotheses formed in this study were as follows:

(1) Shoes with a high bending elasticity reduce the contact time and enhance the propulsive impulse as well as the anterior–posterior and vertical maximum propulsive force during walking, jogging, and running in the active phase.
(2) Shoes with a high bending elasticity reduce the activation of the medial gastrocnemius (GAS) and medial tibialis anterior (TA) muscles in the push-off phase of walking, jogging, and running in the active phase.

(3) Shoes with a high bending elasticity do not influence the kinematics of the lower extremity during walking, jogging, and running in the active phase.

2. Methods

2.1. Participants

We recruited 12 healthy young male adults (age: 24.5 ± 1.2 years, height: 173.13 ± 5.68 cm, weight: 70.27 ± 7.94 kg), who were moderately-trained. All participants were recreational athletes who participated in some form of physical activity at least three times per week for approximately 1 h for each session and had experienced neither lower-limb injuries nor bone nor neural problems within 6 months prior to participating in the test. This study was approved by the Medical Research Ethics Committee of Taipei Medical University Hospital, and all participants signed a statement of informed consent.

2.2. Shoe conditions

Two types of shoe with distinct forefoot designs were adopted: flexible shoes (Nike Free Run 2) and elastic shoes (Nike Free Run 2 + elastic bands, Fig. 1), which were integrated with elastic materials in the forefoot region. The stiffness of the flexible shoes was modified by a shoe technician by adding elastic bands to the forefoot part of the shoe sole to produce the elastic shoes. Participants instinctively selected shoe sizes that best fit them (shoe sizes ranged between 7 and 8 (27 and 28 cm) in intervals of 0.5 in European sizes, and weighed 275 ± 5 g). Participants with foot shapes that did not fit the shoes selected for this study were excluded from the experiment. After the addition of elastic materials, we conducted a stiffness test by adopting bending angles between 10° and 70°, which are the range of MPJ movement angles in human locomotion (Stefanyshyn & Nigg, 1998). A 1-s force-averaging period was set between the third and fourth seconds for each of the three repetitions to ensure a nearly constant value at the fixed angle. The resultant force–angle curve relationship after the addition of elastic materials is shown in Fig. 2. A steeper slope indicated a greater bending stiffness of the elastic shoes.

2.3. Protocol

The participants were informed of all experimental procedures and subsequently asked to sign a consent form. The participants were given approximately 15 min to walk and run to get used to the first pair of shoes. Additional familiarization was permitted if desirable (Sobhani et al., 2013). Before commencing the experiment, the participants were allowed to warm up by jogging at their preferred speed on a treadmill for 10 min. Electrodes connected to the EMG instrument (GAS and TA) were

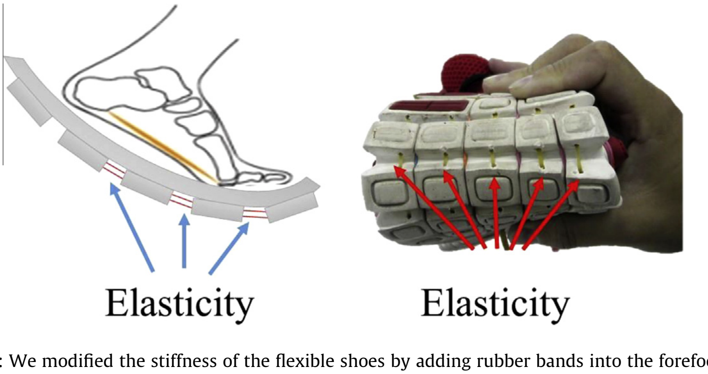

Fig. 1. Elastic shoes: We modified the stiffness of the flexible shoes by adding rubber bands into the forefoot part of the shoe sole.

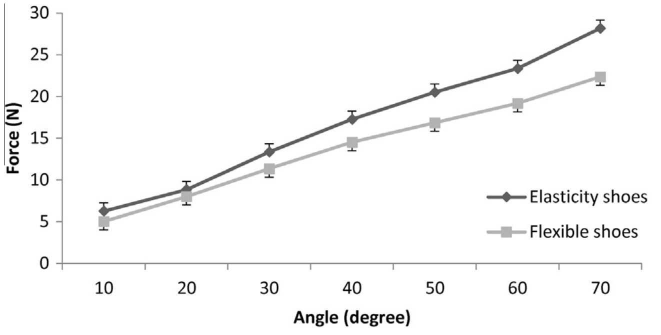

Fig. 2. The force–angle curves, allowing the vertical force necessary to bend the MTP joint at 10–70° to be determined for the elastic shoes (black curve) and flexible shoes (gray curve).

attached to the participants undergoing the maximal muscle strength test. Subsequently, reflective markers were attached to each joint region. The counterbalanced measures design (Sobhani et al., 2013) was employed to test the two types of shoe at three treadmill speeds: walking at 1.5 m/s (average walking speed (Bohannon & Williams Andrews, 2011)), running at 3.5 m/s (similar to the running speed in a study of midsole bending stiffness (Roy & Stefanyshyn, 2006)), and jogging at 2.5 m/s (the speed midway between walking and running). Furthermore, a steady movement for 10 s was captured for signal analysis. Participants were not allowed to see the shoe type before and during the test. Finally, we conducted an indoor track test by using infrared sensors to establish the criteria for speed control; when the speed exceeded ±0.1 m/s, the recorded data was not used. Three successful trials were required for each test.

2.4. Kinematics

The experiments were conducted in a laboratory, using a 3D motion analysis system equipped with 10 cameras (Vicon, UK) and a 200-Hz sampling frequency. Reflective markers (diameter: 1.4 cm) were placed on participants' bony landmarks according to the Plug-in Gait Model (Davis, Ounpuu, Tyburski, & Gage, 1991). The fifth metatarsal and heel–toe markers were placed on the shoes at the positions optimally projecting the anatomical landmarks. All other markers remained at the same positions throughout the testing protocol. The hip, knee, and ankle ranges of motions (RoMs) were calculated using a motion analysis system. The intraclass correlation coefficients of the test–retest measures of walking, jogging, and running for contact time (.847, .900, and .836, respectively), hip (.996, .996, and .990, respectively), knee (.974, .978, and .947, respectively) and ankle (.938, .967, and .940, respectively) RoMs were determined to provide sufficient evidence of substantial reliability.

2.5. Electromyography

The skin where the electrodes were placed was shaved and cleaned with alcohol, and all of the electromyography electrodes were connected to the same ground, which was attached to the lateral femoral epicondyle. The electrode used in this study had two 1-cm-diameter metal plates with 3 cm between centers. Surface EMG (TSD150a, Biopac Systems Inc., USA) involved a high impedance (100 MΩ) and a differential amplifier (common mode rejection ratio = 95 dB; gain = 350). The EMG and Vicon systems were synchronized using an external 5-V square-wave trigger voltage. Electrodes were placed over the following muscles on the dominant leg according to the method of previous study (Perotto & Delagi, 2005). Surface electrodes were used in bipolar derivation to record the EMG activity of the following muscles: The electrode placement on the GAS one hands' breadth below the popliteal crease on the mass of the calf; on the TA four fingers' breadth below the tibial tuberosity; and one finger's breadth lateral to the tibial crest. For the maximal voluntary contraction (MVC) test, participants were positioned on an isokinetic machine (System 3, Biodex Inc., USA) and asked to perform the maximal voluntary contraction and maintain it for at least 3 s in one repetition of the MVC test. The intraclass correlation coefficients of the test–retest measures of walking, jogging, and running for TA (.949, .972, and .932, respectively) and GAS (.945, .949, and .932, respectively) muscle activation were determined to provide sufficient evidence of substantial reliability.

2.6. Kinetics

The kinetic data were collected using a force plate (Kistler, model 9286BA) for recording the ground reaction forces and the contact time at push-off at a 1000-Hz sampling frequency. The intraclass correlation coefficients of the test–retest measures of walking, jogging, and running for propulsive impulse (.924, .896, and .878, respectively) maximal anterior–posterior propulsive force (.835, .905, and .913, respectively) and maximal vertical ground reaction force (.961, .950, and .971, respectively) were determined to provide sufficient evidence of substantial reliability.

2.7. Data analysis

LabVIEW 8.5 (National Instruments, USA) software was used to analyze the kinematic, EMG, and kinetic signals. All the kinematic and kinetic signals were smoothed at a low frequency of 6 Hz. A fourth-order Butterworth filter was used to filter and smooth the EMG raw data. Consequently, the EMG signals were filtered using a band pass filter (10–500 Hz). The signals were then processed using full-wave rectification, smoothed at a low frequency of 6 Hz to obtain a linear envelope graph, and were normalized using the MVC (Fantini Pagani, Willwacher, Kleis, & Brüggemann, 2013; Robertson, 2004).

2.8. Statistical analysis

A paired dependent *t*-test was used to compare the changes in hip, knee, and ankle joint RoMs, contact time, maximum vertical and anterior–posterior propulsive force and propulsive impulse, and muscle activity of the GAS and TA during push-off between the various shoe conditions with the significance level set at $\alpha = .05$.

3. Results

All results are listed in Table 1. For kinematics, the RoM of the ankle of the forefoot bending elasticity shoe were significantly higher than those of the normal shoe for walking ($t = 2.467$, $p = .031$) and jogging ($t = 2.780$, $p = .018$). However, the RoM of the knee and hip exhibited no significant difference among the shoes for walking, jogging, and running. The contact time in the push-off phase was significantly lower for the elastic shoes compared with the flexible shoes for walking ($t = -3.907$, $p = .002$) and jogging ($t = 2.428$, $p = .033$) in the active phase.

For kinetics, the propulsive impulse exhibited no significant difference between the shoes for walking, jogging, and running. The maximal vertical ground reaction force of the elastic shoes was significantly higher than that of the flexible shoes for walking ($t = 2.610$, $p = .024$), and the maximal anterior–posterior propulsive force of the elastic shoes was significantly higher than that of the flexible shoes for walking ($t = 2.592$, $p = .028$) and jogging ($t = 3.231$, $p = .008$) in the active phase.

The GAS muscle activation in the push-off phase was significantly lower in the elastic shoes compared with the flexible shoes for walking ($t = -2.392$, $p = .036$) and jogging ($t = 2.716$, $p = .030$) in the active phase. However, the TA muscle activation exhibited no significant difference between the shoes under all conditions.

4. Discussion

The purpose of the study was to investigate the effect of bending elasticity in the forefoot region of shoes, which might alternate the energy return and kinetics results during the push-off phase.

Table 1
Mean and SD of the movement characteristics in different speeds (walking, jogging, running) and shoes (elastic and flexible) during push-off.

	Speeds	Walking (1.5 m/s)		Jogging (2.5 m/s)		Running (3.5 m/s)		*p*-Values		
	Shoes	Flexible	Elastic	Flexible	Elastic	Flexible	Elastic	F vs. E walking	F vs. E jogging	F vs. E running
Kinematic	Ankle RoM (°)	15.27 ± 4.06	18.45 ± 4.81*	28.65 ± 8.42	34.59 ± 7.08*	22.79 ± 6.16	24.97 ± 6.87	**.031**	**.018**	.227
	Knee RoM (°)	19.10 ± 4.10	20.45 ± 4.10	25.92 ± 5.38	26.13 ± 6.77	25.06 ± 5.63	26.88 ± 7.70	.254	.926	.447
	Hip RoM (°)	16.80 ± 14.32	24.25 ± 13.26	25.70 ± 11.47	31.04 ± 6.14	34.60 ± 11.12	36.44 ± 3.55	.113	.183	.600
	Contact time (s)	0.307 ± 0.020	0.284 ± 0.025*	0.161 ± 0.016	0.154 ± 0.016*	0.134 ± 0.015	0.131 ± 0.016	**.002**	**.033**	.112
Kinetic	Propulsive impulse (Ns)	23.98 ± 4.01	23.86 ± 5.14	14.64 ± 3.53	14.25 ± 3.20	18.77 ± 4.07	18.87 ± 5.05	.845	.424	.880
	Maximal anterior–posterior force (N)	180.98 ± 20.62	186.03 ± 24.47*	170.97 ± 34.56	181.03 ± 31.47*	267.51 ± 50.96	271.03 ± 59.12	**.028**	**.008**	.470
	Maximal vertical force (N)	764.16 ± 84.88	784.74 ± 100.90*	1530.67 ± 246.25	1547.18 ± 218.03	1724.05 ± 324.55	1741.82 ± 246.25	.024	.331	.461
EMG	Tibialis anterior muscle activation (%)	10.18 ± 5.87	9.76 ± 3.95	14.30 ± 4.58	11.61 ± 4.10	20.25 ± 6.47	19.20 ± 5.36	.723	.183	.654
	Gastrocnemius muscle activation (%)	49.01 ± 13.89	43.68 ± 13.53*	68.79 ± 12.12	61.93 ± 9.97*	94.83 ± 13.88	91.93 ± 13.53	**.036**	**.030**	.516

Bold indicates significance ($p < .05$).
* Elastic shoes values were significantly different compared to flexible shoes values ($p < .05$).

According to our results, adding bending elasticity in the forefoot region of shoes not only increases the maximal anterior–posterior and vertical propulsive forces but also decreases the muscle activation of GAS during push-off phase. The phenomenon can be found during normal gait pattern and jogging with moderate intensity. At the same time, we also found that the bending elasticity increases the RoM of the ankle joint and decreases contact time. All these results supported the hypothesis made in this study.

Previous studies showed that the higher stiffness of forefoot region of shoes can alter the RoMs of the ankle and metatarsophalangeal joint resulting power output increasing and shank muscle activation decreasing on jumping, walking and jogging (Chen et al., 2012; Lin et al., 2013; Stefanyshyn & Nigg, 1998, 2000). Furthermore, increasing the bending elasticity in the forefoot region of shoes can improve athletic performance during push-off phase (Stefanyshyn & Fusco, 2004; Stefanyshyn & Nigg, 1998, 2000; Tinoco et al., 2010). It seems more likely that elastic materials in shoes increase the bending elasticity in the forefoot region which can influence GRF lever arms of lower extremity joints during the push-off phase (Willwacher, König, Braunstein, Goldmann, & Brüggemann, 2014); in other words, lowering energy consumption at a specific speed (Roy & Stefanyshyn, 2006). In addition, modifying the forefoot design of shoes facilitates the enhancement of athletic performance (Tinoco et al., 2010; Willwacher et al., 2013). However, designs with increased bending elasticity in the forefoot region of shoes cannot achieve a substantial amount of propulsive push-off impulse, possibly because higher bending elasticity in shoes increases the propulsive push-off force during walking and jogging while reducing the push-off time. Therefore, after increasing the bending elasticity in the forefoot region of shoes, no changes in the propulsive impulse were observed in this study. However, an increase in the push-off force and a decrease in the contact time with the ground enabled a higher bending elasticity to achieve a greater force in a shorter period. Thus, we are confident that in this case the results are in good agreement with previous studies, suggesting that superior push-off performance was obtained (Stefanyshyn & Nigg, 1997, 1998, 2000; Tinoco et al., 2010).

The results indicated that higher bending elasticity in shoes not only changes the kinematic and kinetic parameters of the feet but also influences the activation of the shank muscles. Previous studies have indicated that flexible shoes allow the GAS muscles to have a comparatively greater activation during movements under the same load conditions. Furthermore, a greater load is generated to achieve a superior training effect (Bruggemann et al., 2005; Chen et al., 2012; Goldmann et al., 2013). After increasing the bending elasticity of the forefoot, we showed that higher forefoot bending elasticity expanded the RoM of the ankle joint and subsequently reduced muscle activation, which allowed more energy to be stored (i.e., reduced energy consumption). Therefore, movements using the same amount of strength or energy can decrease muscle consumption to improve running economy. Previous studies have shown that improving the bending elasticity of running shoe soles modifies the location and rotation of the joint axis, thus influencing the changes in joint angles (Smith, Lake, Lees, & Worsfold, 2012; Stefanyshyn & Nigg, 1998). When movements employed identical loads, minimal energy was consumed when improvements were made to the bending elasticity of the midsole of a shoe (Nigg & Segesser, 1992). In addition, greater ankle joint movement in running can reduce energy loss (Stefanyshyn & Nigg, 2000). This result corresponded with the results obtained in this study, where changing the bending elasticity in the forefoot region of shoes expanded the range of motion in the ankle joint during push-off.

In this study, the results showed that when running at a higher speed, significant differences were not observed among the kinematic, kinetic, and EMG parameters. Previous studies have shown that at speeds similar to those adopted in this study (3.13–4.13 m/s), changes to the maximal oxygen uptake, kinematics, kinetics, and EMG are unrelated to the materials of the shoes or the ground surface (Craib et al., 1996; Morgan, Baldini, Martin, & Kohrt, 1989; Roy & Stefanyshyn, 2006; Stefanyshyn & Nigg, 1997; Wank, Frick, & Schmidtbleicher, 1998). As speed increases, the push-off force increases and the push-off phase time decreases simultaneously (Table 1); consequently, the relatively larger force produced in a short period might be too strong for the elasticity of the material. Thus, in this study, we identified that the forefoot bending elasticity design cannot decrease the push-off phase time for running with moderate intensity. However, a limitation of this study was that we have not yet determined a material that provides the forefoot region of shoe with an energy return ability during running. Previous studies have indicated that the incorporation of carbon fiber in the forefoot region of shoes enhances the forefoot bending elasticity, which subsequently constrains the bending angle of the forefoot to reduce energy consumption, ultimately improving the push-off performance (Desloovere et al., 2006; Lin et al., 2013; Willwacher et al., 2013). However, the addition of carbon fiber in shoes is typically accompanied by problems such as concentrated or intense pressure, metatarsal phalange complications, and discomfort (Jarboe & Quesada, 2003). Conversely, we identified that the use of elastic materials can modify the bending elasticity in the forefoot region of shoes and improve the movement characteristics in the push-off phase. Furthermore, we interviewed the participants after the experiments to determine the comfort of the shoes, and all participants responded that they did not experience any discomfort. Therefore, participants' comfort and subjective experiences must be considered when a shoe design using highly elastic materials is adopted.

Useful insights were gained by examining the ground reaction force curves, even though this observation was not based on a statistically significant result. After increasing the forefoot bending elasticity of shoes, larger anterior–posterior and vertical propulsive force peaks were generated in the push-off phase of walking (Fig. 3), but this phenomenon was clearly observed in only one participant; other participants exhibited only slight differences. A previous study reported that distinct participants require shoes with varying bending elasticity to achieve optimal performance. In addition, the ideal sole bending elasticity is related to a person's plantar fascia, shank muscle strength, and the speed of muscle contraction (Stefanyshyn & Fusco, 2004). Moreover, participants' weights also might influence the amount of energy return generated from the forefoot bending elasticity (Roy & Stefanyshyn, 2006; Tinoco et al., 2010). Nonetheless, movement patterns of the forefoot might all be influenced by psychological, physiological, and mechanical factors or participants' own habitual gait movement. Previous studies also showed that the optimal footwear for each athlete is dependent upon their strength, personal force–length and force–velocity characteristics (Stefanyshyn & Fusco, 2004; Stefanyshyn & Nigg, 2000). Thus, the aforementioned result regarding the peak values requires further investigation. However, this observation demonstrated that increasing the forefoot bending elasticity of shoes altered the movement characteristics during push-off of walking for this participant.

By combining previous research results, we determined that the design for training shoes should be different from the shoes for competitive sports. In the development of training shoes, a substantially greater degree of flexibility is required in the design. Consequently, at the same training intensity, greater load can be provided to the calves and feet and a superior training effect can be achieved (Bruggemann et al., 2005; Goldmann et al., 2013). However, according to the results of this study, shoes for competitive sports must possess an enhanced ability to return energy and reduce energy consumption to improve movement characteristics. Previous research has also indicated that if 2% less

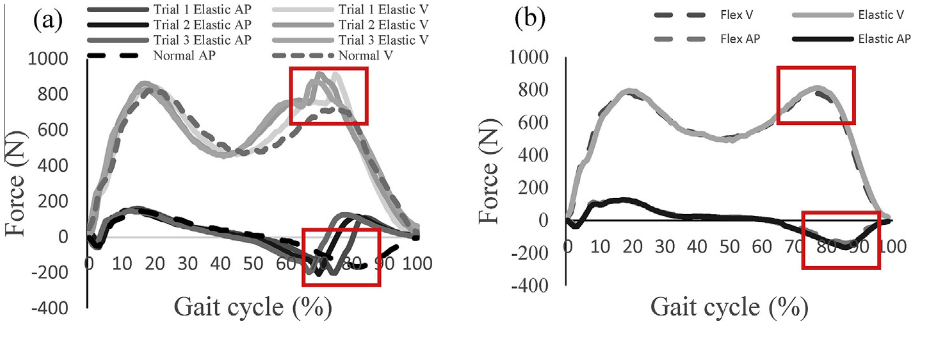

Fig. 3. (a) The ground reaction force of one participant wearing elastic shoes shows that the anterior–posterior and vertical propulsive force peaks were generated in the push-off phase of walking; the solid lines indicate three successful trials of elastic shoes and the dotted lines indicate the curves of flexible shoes. (b) The ground reaction force of other participants wearing either elastic or flexible shoes shows no anterior–posterior and vertical propulsive force peaks being generated; the lines indicate walking with elastic shoes in anterior–posterior directions (Elastic AP), vertical directions (Elastic V), and with the flexible shoes in anterior–posterior directions (Flex AP), and vertical directions (Flex V).

energy is consumed for every step taken, a total of 500 J can be reduced during a marathon (Nigg & Segesser, 1992). Therefore, the development of a design for the forefoot region is crucial. In summary, we placed a highly elastic material in the outsole of shoes to enhance the ductility of the material before push-off, increase the energy-return effect of the material after push-off, and ultimately improve the movement characteristics during push-off.

5. Conclusion

In conclusion, the results of this study showed that the addition of elastic material in the forefoot region of shoes not only reduced activation of the GAS muscles but also enhanced both maximal anterior–posterior and vertical propulsive forces in the push-off phase to reduce push-off time. However, at an increased running speed, the elastic material cannot provide additional energy return during push-off. Thus, a stronger elastic material is necessary to provide an optimal energy return at higher running speeds. Future studies can therefore focus on identifying a forefoot bending elasticity that is suitable for intense movements and generates energy return at higher running speeds or various jump conditions. Finally, studies should endeavor to evaluate the primary factors that influence the forefoot movement during push-off.

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